APPENDIX D
Astronomy

INTRODUCTION

The potentially useful role of man in space astronomy is described in this paper on the basis of certain fundamental assumptions that are believed plausible in the post-1975 period. Justification of manned space flight is not intended; rather, the purpose here is to describe what man could do, if he were available. The fundamental assumptions are:

1. Logistics and rendezvous are cheap and safe, from the Earth and from interorbit shuttlecraft.
2. Man is as useful in space as on Earth, providing that the man-machine interface has been properly designed.
3. Continuously manned stations are available in space, in low orbit, in synchronous orbit, and/or on the lunar surface.

The need for the availability of telescopes in space for astronomical research has been expressed by many scientists (e.g., refs. 4, 5, 33, and 34). Of primary importance to understanding the physical processes that take place in the universe is the accessibility afforded by space to whole regions of the electromagnetic spectrum that cannot be detected from Earth. Wavelengths shorter than about 2900 Å and longer than about 60 meters cannot penetrate to the Earth's surface at all, and only limited spectral regions in the wavelength range between about 0.8 microns and 8 millimeters are visible through the Earth's atmosphere. In the spectral regions that can be seen from Earth, spatial resolution is also limited, because the Earth's turbulent atmosphere restricts the angular resolution to about 1 arc-sec in the optical and millimeter regions. Variability of transmission, scattering by the Earth's atmosphere, airglow, and auroral emission limit the accuracy of any intensity measures at optical wavelengths of astronomical objects, and consequently limit

also the degree of faintness to which one can see and the time resolution that is possible for transient and rapidly varying astronomical phenomena.

A space observatory would allow astronomical observations of very high angular resolution, ultimately limited only by the imaging properties of the telescope over the entire electromagnetic spectrum. Accuracy of intensity measures and time resolution would not be limited by the Earth's atmosphere. The faint limit of instruments would be determined by the instruments themselves, or by extraterrestrial "noise," such as zodiacal light, galactic background, Lyman-alpha emission, or plasma oscillations of the interplanetary medium.

In this paper, the scientific goals of astronomy are briefly stated first in very broad terms, because they have been discussed in detail in the reference publications. The instrumentation that is considered necessary to accomplish the scientific goals is described next. Farther on, man's general role in space astronomy is outlined, and his specific function with the described instruments is explained. There follows an enumeration of the relative scientific merits of low Earth orbit, synchronous orbit, and lunar base for various types of observation. The final two sections present some critical questions and end with conclusions and recommendations.

GOALS AND OBJECTIVES OF ASTRONOMY

The goals and objectives of astronomy have been described in various places, such as the "Woods Hole Report" (ref. 1), NASA "OSSA Prospectus" (ref. 2), the "PSAC Report" (ref. 3), and by Spitzer (ref. 4), Kopal (ref. 5), Tifft (ref. 6), and most recently by various panels of the Astronomy Missions Board.* From the PSAC Report, we quote the following concise statement of questions that can be studied by astronomical techniques:

1. Does life abide in places other than the earth, and if so what is its nature, how did it evolve, and what are its possible forms elsewhere?

*The Astronomy Missions Board, Leo Goldberg, *Chairman*, has formed the following panels: X-Ray and Gamma Ray: W. L. Kraushaar, *Chairman*; Radio: B. F. Burke, *Chairman*; Solar: J. W. Evans, *Chairman*; Optical: L. Spitzer, *Chairman*; Planetary: J. W. Chamberlain, *Chairman*; and Fields and Particles: J. A. Simpson, *Chairman*. These panels are advisory to the Board, which has to review and approve their recommendations and forward them to NASA.

2. What is the origin and evolution of the Universe, and what is its ultimate destiny? What is the place of our sun and solar system in it? Do natural laws as we know them on earth indeed govern the behavior of every observable part of the vastness of space?

3. What are the physical conditions on the moon and on the other planets in our system, and how did our solar system evolve? What dynamic relationships between the sun and the planets shape their environment?

The scientific objectives of astronomy can best be approached with specific types of instrumentation. The "Woods Hole Report" (ref. 1), the "OASF Study" (ref. 7), and the General Dynamics Study (ref. 8) describe instrumentation goals that will allow us to handle the scientific questions.

A program for developing astronomical instrumentation should be designed to place the following major instruments (ref. 1) in space in the next 10 to 15 years to cover the more than 20 decades of the electromagnetic spectrum (from 10^{25} hertz down to 10^{3} hertz).

A. An optical space telescope of very large diameter, with a resolution corresponding to an aperture of at least 120 inches [studied in more detail by the Spitzer Large Space Telescope Committee (ref. 4)].

B. An optical solar telescope of 1- to 1.5-meter aperture with a focal length of 50 to 75 meters.

C. An XUV solar telescope of about 1-meter aperture, designed to operate from about 1500 Å down to 300 to 500 Å. It must not have folded optics. This instrument is unique to solar astronomy, because it is predicted that interstellar matter is opaque to Lyman continuum radiation (below 912 Å). It is important, however, to verify this by using the XUV solar telescope for some stellar observations.

D. A coronagraph with an external occulting disk. Because of the extreme dynamic range from the inner to outer corona, at least two coronagraphs of different aperture would be required.

E. A grazing incidence-focusing X-ray solar telescope. Because the solar flux between 1 and 500 Å (where this instrument is effective) is high, a small-diameter instrument, about 20 centimeters, is adequate.

F. A grazing incidence-focusing X-ray telescope for observations of galactic and extragalactic sources. An aperture of at least 1 or 2 meters is required: the Woods Hole Report recommends a diameter of 10 meters; however, nested mirrors offer a more reasonable approach (ref. 9). The focal length is at least 10 times the aperture.

G. A large array of gas-filled proportional counters to cover the energy range from approximately 1 to 50 keV. These arrays, with collecting areas of 10 or more square meters, would be mechanically collimated to arc-minutes. Collimation becomes more difficult as the size of the array increases, but observations of very faint sources are desired, and hence large arrays are needed. This 10-square-meter array might thus be augmented to 100 square meters, but with a collimation of only a few degrees for the overall array.

H. A 1-square-meter array of lithium-drifted germanium crystal detectors for observations in the energy range from about 50 keV to a few MeV, mechanically collimated to an arc-minute. New techniques can be expected to allow larger, more sensitive arrays.

I. An array of scintillation crystals up to 10 square meters in area would be usable in the difficult energy range between about 3 and 10 MeV. Collimation is difficult because X-rays of this energy can pass through thin collimator materials. New techniques can be expected for all the higher energy observations in the MeV and multi-MeV range.

J. An array of cubic-meter spark chambers to detect gamma rays in the 10-MeV to 1-BeV range. Ten to a hundred such spark chambers would be used in the array. Each spark chamber would most likely be limited to about 1 cubic meter to avoid dead-time problems.

K. A large Cerenkov counter with a volume of thousands of cubic meters for gamma rays above 1 BeV.

L. A large millimeter-wave and longwave infrared telescope with an aperture of 10 meters or more for nonsolar observations in the wavelength region between a few millimeters and 10 microns.

M. A very large longwave radio telescope for observations at frequencies below the ionospheric limit of about 30 MHz. This would most likely be a filled-aperture (rhombic) antenna of 10 kilometers (ref. 10).

The instruments described above for hard X-ray and gamma-ray astronomy (G through K) are based on current techniques. Several of the instruments are described in the "Kraushaar Report" (ref. 11). Innovations in these areas are likely and might significantly alter the instrumentation used, such as the recently proposed X-ray and gamma-ray scatter-hole camera (ref. 12).

Other instruments of potential value are:

1. Optical stellar interferometer, either of the Hanbury-Brown and Twiss type or the Michelson type (refs. 13 and 14).

2. Solar millimeter telescope. To obtain high resolution at this wavelength without too much heat input will probably require an interferometer or a partially filled aperture. It might be possible to mask the instrument described in item L to perform as a partially filled aperture.

All of these instruments are technologically feasible in the post-1975 time period. They are major instruments that are required to reach into new frontiers of scientific research. Each of these major instruments must be supported by ground-based telescopes and by other smaller space telescopes. Tasks that can be performed by smaller special-purpose instruments should not occupy the time of the very large telescopes.

ROLE OF THE MANNED PROGRAM

In the Goals of Astronomy section, 13 specific telescopes were described which cover the electromagnetic spectrum from a frequency of about 10^3 hertz to 10^{25} hertz. In this section, the possible role of man in connection with each of these instruments will be described. Innovations in technique and instrumentation may alter specific tasks, but the general role of man in connection with instruments performing a specific function in a specific spectral region will probably not be altered significantly.

GENERAL ROLE OF MAN

Observational astronomy is wholly data collecting; we are interested in knowing the flux in a given frequency and the direction from which it comes. In some cases, we are further interested in phase and polarization information. Because we want to obtain this data with the most efficient use of time, the instrumentation is automated to the greatest possible extent. In ground-based observatories automation is being introduced gradually, as funds and technology permit. Any space astronomy would essentially be completely automated. It is too expensive to have man using valuable time to point at stars, operate filter wheels, or reset shutters. Man is not infallible in recording times, positions, or dial settings; hence, all these operations must also be automated, as they are done in modern Earth-based astronomy.

Even completely automated systems, however, cannot operate without the assistance of man. Man alone is the general systems overseer, diagnostician, and repairman. He is a "supertechnician," without which complex automated systems could not function long. Man's role with automated instruments can be divided into the following categories: maintenance/repair, retrofit/replacement, deployment/checkout, alinement/calibration, and operation/data management. Man's general usefulness in these areas has been studied by the Perkin-Elmer Corp. (ref. 15), the Boeing Co. (refs. 16 to 18), McDonnell-Douglas Corp. (refs. 19 and 20), Lockheed Missiles & Space Co. (ref. 21), the Space Station Requirements Steering Committee (ref. 22), and others.

Each of these areas encompasses the following activities, broadly stated:

Maintenance/Repair

Automated space astronomical instruments should be designed for modular maintenance, because a manned visit may be deemed possible, even if not originally planned. The most vulnerable parts of an instrument (e.g., a photomultiplier, a thin-window X-ray detector, or an offset guider) must be readily accessible for maintenance. In some cases, single units might be repaired, but generally we would picture replaceable plug-in modules, much as modern computers are repaired. As with computers, any sophisticated space instrument should have built-in diagnostic procedures, so that man might perform preventive maintenance by replacing weak sensors or faulty amplifiers, thereby permitting failure analysis.

Retrofit/Replacement

One of the most difficult design problems of a sophisticated automated instrument is to envision the parts that will become obsolete. However, this must be done with any large space instrument, so that man may update the instrument by replacing old detectors with more sensitive ones, or retrofitting a telescope with a new state-of-the-art spectrograph or reflection grating. Thus, if an instrument is properly designed, man can play a very important role in prolonging the productive life of that instrument and providing it with versatility by keeping it up with the state of the art, or modifying it to perform the science of most current interest.

Deployment/Checkout

Here there will be a great variety of one-shot tasks that are involved with the initial deployment of an astronomical instrument. Most instruments will be launched readymade and automatically deployed, so that man's function will be primarily a visual inspection to insure structural integrity and proper deployment. This "eyeball" checkout is an important task that cannot be eliminated except by use of a TV camera with the mobility and discrimination of man. Delicate instruments, such as telescope mirrors or X-ray detectors might be specially blocked or packed for launch, and would require man's assistance in deployment. Instruments which exceed spacecraft dimensions, such as large area X-ray arrays or large optical or focusing X-ray telescopes, might require man to assemble major subsections.

Alinement/Calibration

Alinement and calibration, which will be done both initially and probably periodically, will probably be mostly automated. A sensitive optical instrument must be alined and calibrated in the same environment under which it will normally operate, so that in most cases man will not be involved. Initial coarse alinement might be necessary, if after launch and deployment the instrument is misalined beyond the range of any automatic system.

Operation/Data Management

As previously discussed, man in space may have little part in functioning as an actual observer or as part of the data-collection procedure in nonsolar and low-resolution solar astronomy. Naturally, we would have man perform periodic checks on the observations, presumably by selective data readout, to insure that all was operating normally, as perceived by human judgment. Operation and data collection would all be computer run under ground control, with the computer programed to point the instrument and record all pertinent data. Any "target of opportunity," such as a supernova or new comet, could be easily programed in as long as there was a good communication link with Earth. Man's much-discussed role as a film-handler is not considered here. It is presumed that in the post-1975 period electronic imaging will be the

major mode of image recording. If this is not the case, then many of the optical, XUV, and X-ray telescopes will probably require regular visits for change of film.

For high-resolution observations of the Sun, man can play an important role in the pointing/data-collecting loop by selecting only those areas of the Sun that are of special interest. These are generally low-contrast areas, such as plages, filaments, sunspots, etc., where man's judgment is very useful. If a broadband communications link is available, man's physical presence at the telescope may not be necessary.

SPECIFIC ROLES OF MAN

Optical Nonsolar Astronomy

The 120-inch telescope described in item A under Goals of Astronomy is used for this type of astronomy. To be versatile, this telescope will have at its focus the following general types of instruments: (1) spectrographs/spectrometers, (2) photometers, (3) cameras (field-imaging; possibly with film, but with electronic techniques as soon as possible), and (4) polarimeters.

The large-aperture telescope will be of extreme importance to astronomy, and can be used for its entire operating lifetime. The instrumentation at the focus will change from time to time as we develop new ideas and new techniques. This telescope would probably not be operated in physical conjunction with any other equipment, to insure freedom of pointing. Because of the extremely precise nature of this instrument, man will generally play little, if any, role in the actual operation or in precision alinement. General monitoring of observations would be performed to check on inconsistency or unexpected results. On the other hand, the delicacy of these instruments may require that man play an important role in keeping them operating, by performing some routine preventive maintenance and being available to repair any system malfunction. As was pointed out, the optical telescopes themselves would be expected to have long lives, but instrumentation at the focus would be changed as new technology or new techniques evolved, thus giving man the important duty of changing instruments and updating these telescopes. Deployment procedures would probably be minimal, unless possibly certain sensitive components were specially

packed for launch, or the telescope structure was too long to launch as one unit.

Millimeter Astronomy

The infrared telescope described in item L under Goals of Astronomy is used for this mode of operation. Most of the optical astronomy discussion applies here. The equipment is not quite as precise, at least in terms of absolute dimensional tolerances. However, the sensors are generally very delicate, and deployment might involve installation of the sensors. Because this equipment must operate at extremely low temperatures, man would be necessary to replace or refill cryogenic storage on the telescope/spacecraft (his presence is undesirable during operation because of the heat he radiates). Updating of sensors will be very important in millimeter astronomy, because the technology is in a great state of flux. The dish is so large that man might be required to assemble it, perhaps by attaching various sectors together.

Long-Wavelength Radio Astronomy

The rhombic antenna described in item M is used here. Man would probably be least involved in this area. The telescope is large, and mechanical tolerances are not critical. The instrumentation consists of suitable amplifiers, which can be quite reliable. Therefore, man would probably be involved only in visual inspection of the automatic deployment of the instrument in orbit and in very infrequent maintenance. If large radio telescopes are to be deployed on the lunar surface, man will necessarily be involved in their construction.

Gamma-Ray Astronomy

The spark-chamber array and Cerenkov counter described in items J and K are used. The spark-chamber array and the Cerenkov counter itself would be assembled by man, because they are so large. Maintenance could involve gas-refilling and repairing any meteoroid damage. There will probably be little retrofitting, since in this field complete new systems are more likely. Man would not be involved in the operation.

Hard X-ray Astronomy

The arrays described in items G, H, and I are employed in this operation. Some X-ray astronomers feel that man will probably play a limited role. Very large arrays may have to be assembled in space by latching together manageable-sized portions of the array. Retrofitting would most likely involve new collimators or new detectors, but completely new systems could be expected in this new frontier.

XUV and Soft X-ray Astronomy

The instrument described in item F is employed. The focusing X-ray telescope would probably be quite permanent, like the large optical telescope, and man would play an important role in updating, changing, and maintaining the instrumentation at the focus. As in millimeter astronomy, cyrogenic resupply could be important. Man would probably play no significant role in operation, but the telescope may be too long to be launched in one piece, thus requiring man to assemble the tubular sections in space.

High-Resolution Solar Astronomy

This type of solar astronomy involves unique use of man, with the following co-located (and possibly optically alined) instruments: (1) optical telescope, as described in item B; (2) XUV telescope, as described in item C; and (3) focusing X-ray telescope, as described in item E.

As with all other instruments, man will maintain and update these three "permanent" solar telescopes. The optical and XUV telescopes may be so long as to require manned assembly.

Solar astronomy (and possibly high-resolution, Earth-orbital planetary astronomy) is unique for man as an observer because we want to observe specific low-contrast features with a detector that has a spatial resolution significantly finer than the target at which we are looking (the Sun or a planet). Rather than taking automated high-resolution scans of the entire target, we can use man to improve significantly the data-taking efficiency by selecting only "pertinent" areas to observe. The best way to accomplish this would be to provide the observer with a visual display of the Sun in some specified wavelength region, with the observing aperture (e.g., spectroscope slit or spectroheliograph scan area) superimposed. The

observer, with a servo control, could move the aperture to any desired area (in reality, slewing the telescope), and have the capability to zoom to the point where the aperture essentially fills this field of view. There is no reason why the observer need be physically located at the telescopes. Continuous TV communication is required, which is possible either: (1) from nearby, as a space station in a similar orbit, or from a lunar base if the telescopes are on the Moon; (2) from the Earth if the telescopes are in Earth-synchronous orbit; or (3) from the Earth via a data-relay satellite if the telescopes are in low Earth (possibly Sun-synchronous) orbit.

Low-Resolution Solar Astronomy

This type of solar astronomy involves instruments that stay Sun-centered, such as: (1) a coronagraph (as described in item D); and (2) whole-Sun imaging instruments in various wavelength regions.

Such instruments generally will not be man operated, but will, of course, depend upon man maintenance. The coronagraph requires a very long boom with carefully alined occulting disks. Man may be necessary in the deployment of the coronagraph and possibly in the alinement, although automatic alinement should be possible.

OBSERVING SITES FOR ASTRONOMY IN SPACE

According to the fundamental assumptions of this study, the following observing sites are equally accessible, although the cost per pound may be considerably different (approximate ratio 1:3:10): (1) Low Earth orbit (200 to 300 nautical miles), (2) synchronous orbit (19 350 nautical miles), and (3) the lunar surface. The scientific advantages and disadvantages of each site will now be described. Most of the publications referenced so far in this paper have dealt primarily with low Earth orbit, since that is presently the only economical location for large payloads. Except for a Boeing Study (ref. 18), the merits of synchronous orbit have only briefly been described to date; e.g., Spitzer (ref. 4), Tifft (ref. 6), and the Woods Hole Report (ref. 1). Considerably more attention has been given to the merits of lunar-based astronomy. Of particular interest are Tifft (ref. 6), the "Santa Cruz Conference" Report (ref. 23), and the "Falmouth Conference" Report (ref. 24).

With few exceptions, all of the astronomical instruments described in the "Goals and Objectives of Astronomy" section (p. 52) can operate and yield extremely valuable new scientific data from any of the three sites. However, each type of instrument has certain unique properties and requirements that will determine which site is better.

Low Earth orbit clearly has few advantages when we are not constrained by launch costs, except for X-ray and gamma-ray astronomy. The latter have the advantage that the Van Allen belts shield a low orbit from high-energy solar protons. However, even low orbit is not free from radiation, because of the extensive South Atlantic anomaly. Major disadvantages of low orbit are:

1. Passing through the Earth's shadow, every orbit will create thermal cycling problems, especially with the large structures envisioned here.
2. Earth occultation may interrupt viewing as frequently as every 50 minutes.
3. Ground communication is more difficult, especially if we want real-time TV linkage and experiment control.
4. Gravity gradients and airdrag may create engineering and orbit-keeping problems with these large structures.
5. There is sufficient residual atmosphere to affect some observations, especially between about 400 and 800 Å.
6. Some amount of airglow and aurora occur at low-orbit altitude and even higher altitudes.
7. Large orbital velocity, in a continuously and rapidly changing direction, produces appreciable Doppler and relativistic aberration effects when high-resolution spectral or spatial work is important.

The lunar surface is potentially very advantageous for radio astronomy (ref. 25), where we need exceedingly large structures and a radio-quiet environment, outside of the Earth's magnetosphere. It is clearly disadvantageous for solar astronomy, because each 2 weeks of "day" is followed by 2 weeks of "night." There are several special interest observations that are probably done most easily on the Moon, using the lunar horizon as an occulting edge. We can, just after sunset or just before sunrise on the Moon, (1) study the outer solar corona without worrying about instrumental light scattering problems; (2) study the planet Mercury and highly eccentric comets without concern for the proximity of the Sun; and (3) measure the relativistic bending of starlight.

In X-ray and gamma-ray astronomy, the use of the lunar horizon, sweeping across the sky at a low angular rate, can assist in locating

more precisely these high-energy sources. A problem, however, is that the lunar albedo is high in the very high energy regions, and that the occulting horizon will be a contributor to the gamma-ray background, being possibly 10 times greater than the isotropic background itself. Thus the use of the lunar horizon as an occulting edge for gamma rays will be limited to reasonably bright sources.

Tifft (ref. 6) has presented the best case for doing optical nonsolar astronomy on the Moon. Accordingly, it is appropriate to discuss his work.

Geometric Factors.–The Moon has the advantage of guaranteeing 14 days of total darkness, during which nearly half the celestial sphere is accessible. General sky accessibility is difficult to evaluate. On the Moon, there may be a delay of 14 days before one can view in a given area (e.g., a supernova). In high Earth orbit virtually any area is immediately accessible, unless in the proximity of the Earth, Moon, or Sun. Tifft has presumed that any object less than 45° from the limb of the Sun, Moon, or Earth is inaccessible. To view down to 20° of the Sun or sunlit Earth would require providing a lightweight tubular baffle that extends in front of the secondary mirror-support structure a distance of 2.9 times the telescope aperture, in order to prevent any thermal warping of the secondary mirror support or prevent any light scattering from it. Since the Moon is considerably less intense from Earth orbit, its limitation angle might be about 10°. If this is true, 90 percent of the celestial sphere is accessible at any instant from synchronous orbit, in comparison to about 45 percent from the lunar equator. If complete absence of sunlight and earthlight is required for some types of observations, then the back-side of the Moon is the only reasonable site.

The unique problems of solar astronomy were previously discussed. The Moon is most suitable for these observations.

Orbital Doppler shift and aberration of starlight are much more strongly marked in Earth orbit than on the Moon. It should not, however, be difficult to account for the changing Doppler velocity component with a slowly rotating element in the spectrograph. In synchronous orbit, the half-angle of the field of view of a 120-inch telescope at 5000 Å would be limited by relativistic aberration to about 18 arc-minutes, on a long exposure. This again may not be a serious limitation, since geometric optical aberrations may well limit the field even more. Most high-resolution studies will be over

very small fields of view (multiple stars, galaxies, planets) until large-area, high-resolution detectors are perfected.

Environmental Factors.—The radiation environment of space is detrimental to man and film. As was already pointed out, low Earth orbit, except for the South Atlantic anomaly, offers the best natural shield from energetic particles. By preparing underground shelters and storage areas, the Moon offers protection from energetic cosmic particles.

The thermal environment in low Earth orbit is the least desirable of any site, because of repeated 45-minute cycling in and out of the Earth's shadow. In high orbit, a great degree of thermal equilibrium can be established, because the telescope is in direct, uninterrupted sunlight for about 6 months. It only passes through the Earth's shadow when the line of nodes of the satellite's orbit points near the Sun. The Moon also thermally cycles, but at a much slower rate than low Earth orbit cycling. It should be possible on the Moon to build a large structure to maintain constant shadow on the telescope.

Because there is no evidence of an intrinsic lunar magnetic field, the Moon certainly represents a superior low-magnetic environment. In synchronous orbit, the Earth's magnetic field is about one one-hundred-and-eightieth that of the surface. On the Moon, it is more than 1000 times less than at synchronous altitude.

The microparticle environment due to primary particles is essentially the same on the Moon and in synchronous orbit. The main concern is degradation of optical surfaces, and this depends on the solid angle of space that the mirror sees. Theoretical considerations show that secondary ejected particles on the Moon will generally follow low trajectories and be of consequence to a lunar telescope only when pointing near the horizon. Such near-horizon viewing is one of the special reasons for lunar-based telescopes.

The optical environment must be very good for faint astronomical work. As has been mentioned previously, low Earth orbit is undesirable for some wavelengths because of residual Earth atmosphere. At synchronous altitude, spacecraft effluents are of serious concern, because the telescope will be in continuous sunlight. With careful engineering design, it seems possible that sufficiently low optical absorption and background can be realized even with a manned spacecraft. A lunar-based observatory would be just as susceptible to local contaminants (except for reaction control jets).

Evidence of a possible lunar atmosphere or dust haze is inconclusive at the present time. Since the zodiacal light, even at the ecliptic poles, is about 4×10^{-14} the brightness of the Sun, any local background does not need to be much lower than that, especially if its time variation is slow.

Operational Factors.–The Moon may provide a very stable base upon which to provide 0.01 arc-second or better guidance for large telescopes, especially interferometric telescopes. All present evidence is that the Moon is not seismically active.* But if the Moon is not stable–if there is constant microseismic activity like that on Earth–then such fine guidance may be best provided in orbit. Engineering studies (e.g., Perkin-Elmer, (refs. 15 and 26) indicate that extremely accurate pointing precision is possible in orbit.

An operational man-machine interface might be easier on the Moon. One would picture a lunar observatory intimately associated with a manned lunar base. However, all the preceding discussion has shown that we generally do not want man in the operational loop. For shirt-sleeve maintenance, it may be no more difficult to fly a "garage" to the orbital telescope than it would be to build a pressurizable observatory dome on the Moon.

Because of the extreme cold available during the lunar night, millimeter astronomy, especially to very low signal levels, might best be done on the Moon during the night. A very large antenna for millimeter astronomy might be constructed to be essentially fixed on the Moon, much as the Arecibo Observatory is constructed.

Communication with ground-based astronomers is most limited in low Earth orbit, probably less limited on the Moon, but certainly least limited in synchronous orbit.

To summarize, we find that generally one site cannot be used to attack all astronomical goals, but neither can one site be ruled out as not assisting in the attack on any goals. Various instruments are needed at all three sites, as described below:

1. Optical nonsolar astronomy. Several special-interest studies would profit from a lunar-based observatory, but one cannot depend on doing all high-resolution and dim-light astronomy on the

*The passive seismic experiment emplaced on the Moon by the Apollo 11 astronauts indicates that the Moon may be seismically active. (Note added in proof.)

Moon (or in synchronous orbit) until more is known about each environment. The Moon might be especially attractive as a solid base for an optical interferometer.

2. Millimeter astronomy.There is no clear-cut difference between the Moon and synchronous orbit. However, the Moon may have the advantage of allowing a very large fixed dish to be constructed with a movable "feed," and operable only during lunar night.

3. Long-wavelength radio astronomy. The Moon may be advantageous as a support for extremely large filled-aperture radio telescopes many kilometers in extent, depending upon the nature of the lunar surface and any possible atmosphere. Such astronomy is impossible below synchronous altitude.

4. Gamma-ray astronomy and X-ray astronomy. Low Earth orbit has the advantage of low background and is where general survey work with large arrays should be conducted. Special purpose less extensive arrays would be useful on the Moon for finer position determination using the lunar horizon as an occulting edge. A large focusing X-ray telescope might best be in synchronous orbit, because its size would require the small gravity gradients and thermal stability available there, assuming that the detectors could be adequately shielded. Such a structure probably could not operate under lunar gravitational conditions.

5. Solar astronomy. Synchronous orbit clearly has the advantage of about 99 percent annual solar visibility, compared to about 50 percent on the Moon and even less effective time in low orbit. A Sun-synchronous low orbit will yield nearly 100 percent solar visibility, but it is subject to all other low-orbit drawbacks already enumerated. However, the small focusing X-ray telescope for solar viewing is the only instrument that might better be placed in low Earth orbit to avoid the effects of the solar wind. The Moon is advantageous as a site for studying the outer corona.

CRITICAL ISSUES

The development of the instruments described in the "Goals and Objectives of Astronomy" (p. 52), and their use in answering our questions about the universe depends on supporting research and technology in many areas and also on the answers to several critical questions. The areas of supporting research and technology development required have been described in the OASF Study (ref. 27),

Woods Hole Report (ref. 1), Astronomy Program Memorandum (ref. 28), the ASTRA (Astronomical Space Telescope Research Assembly) Study (ref. 29), and by the Astronomy Missions Board. The list of important developmental areas is too extensive to enumerate here. What will be considered are certain critical questions, the answers to which could produce major changes in program direction.

Should the various major high-resolution and high-sensitivity astronomical instruments be integral monolithic structures or modular, and possibly active? This general wording includes these specific questions in various subdisciplines:

1. Should a large diffraction-limited telescope be monolithic or segmented? Should it be passive or active?
2. Should a focusing X-ray telescope of large collecting area be one very large aperture mirror or nested mirrors of smaller aperture?
3. Is aperture synthesis possible at radio wavelengths on the order of kilometers, or must we use one very large antenna?
4. Are arrays of smaller spark chambers better than one large spark chamber? The same question can be asked about Cerenkov counters.

Some of these questions must be determined by building and operating in space prototype, scalable instruments. Theoretical investigations are also important, but may not be definitive in all instances.

Can dim-light astronomy be done in direct sunlight? We have no definitive measures of how dark space is.* The darkest part of the zodiacal light (at the ecliptic poles), as determined from the Earth, is about 4×10^{-14} of the solar disk brightness, or about 22.8 mag/(arc-sec)^2. It must be determined if the effect of sunlight on the spacecraft and on any possible spacecraft coma can be kept below this level.

What is the lunar environment as it pertains to astronomy? It is imperative that we determine the following about the Moon before we can consider large astronomical instruments there:

1. What is the radiation level (X-ray and gamma ray) of the lunar horizon?

---

*Observations made with OAO-II are establishing the background light levels in space. (Note added in proof.)

2. What is the lunar magnetic field, if any?

3. What is the bearing strength of lunar soil: how deep is "bedrock?"

4. What is the nature of lunar seismic activity, if any?

5. What is the flux, angular distribution, and size distribution of secondary meteorites?

6. Is there a lunar atmosphere or dust haze?

7. What is the dielectric homogeneity of the lunar surface?

What is the best man/machine interface? There are certain critical questions that can only be answered by testing systems in space:

1. Can a telescope operate in the immediate presence of man in space? We are concerned about pointing, optical environment, and thermal balance. The ATM-A can provide some answers to these questions; however, any failure of ATM-A on these counts does not necessarily mean that it is impossible to operate a telescope near man.

2. What is the best way to maintain a large scientific instrument in space? Should we plan on any normal EVA? Would the maintenance shuttle be a huge garage, engulfing the entire instrument to be repaired, or should the scientific instrument be designed with a docking port and a pressurizable walk-in instrument compartment?

These critical questions must be answered as soon as possible to prepare the way for the large astronomical instruments. The Orbiting Astronomical Observatory can assist in determining sky brightness and the potential of dim-light astronomy in the Sun. The possibility of OAO/man interfaces has been investigated by Hallam (ref. 30), Perkin-Elmer (ref. 15), Grumman (ref. 31), and Kollsman Instrument (ref. 32). The OAO is too small to answer all questions regarding interfaces with man, and too small to test many prototype instruments. The ATM and the proposed ASTRA (ref. 29) offer a much better capability for determining whether we need passive or active large mirrors, whether we can use nested, focusing, X-ray telescope mirrors, and what should be the interfaces with man.

As early as possible in the lunar exploration program we must determine the astronomical environment of the Moon. As on Earth, some lunar sites may be more desirable than others, so that several landing sites should be tested.

CONCLUSIONS AND RECOMMENDATIONS

The availability of man in space is indispensable to the continued, efficient operation of complex astronomical instruments in space.

Man does not *need* to play the role of observer in space. In situations where man is required in the observation program (as in high-resolution solar astronomy), the transmission of TV pictures to scientists on Earth and the ability to point the telescopes from Earth may be desirable as the normal manned operation mode.

To observe over the entire electromagnetic spectrum, a great variety of instruments is needed. The ideal program would call for these instruments to be situated in a variety of locations; low Earth orbit, Earth-synchronous orbit, and on the Moon. However, a viable program could certainly be carried out with the major instruments located exclusively in orbit or exclusively on the lunar surface.

To determine the best instruments to use for space astronomical research, the best places to locate them, and the best use of man, several critical decisions must be made, based upon actual, manned, astronomical investigations in orbit and on the Moon. These decisions involve: (1) integral versus modular instruments, (2) active versus passive optics, (3) dim-light astronomy in sunlight, (4) the Moon as an observatory site, and (5) the nature of man-telescope interfaces.

It is recommended that, to make these decisions, immediate effort be made to build and operate in space prototype, scalable telescopes and other astronomical instrumentation, in such programs as ATM and ASTRA, for optical, solar, X-ray, gamma-ray, and millimeter astronomy. All scientific satellites should be designed for modular maintenance, even if there is no intent for man to visit them in space. This would provide for experience in such construction techniques, the possibility of repair if it were later deemed advisable, and simplified environmental testing.

It is recommended that any lunar exploration program include an astronomical site survey, including the deployment of a large radio telescope on the lunar surface, to seek answers to the questions presented in "Critical Issues" (p. 66).

REFERENCES

1. Space Research—Directions for the Future. Report of an SSB Study. NAS-NRC (Woods Hole, Mass.); Part I—1965, Part II—Jan. 1966.
2. Goals and Objectives in Space Science and Applications. OSSA draft prospectus, Mar. 1968.
3. The Space Program in the Post-Apollo Period. Report of the President's Science Advisory Committee (PSAC Report), Feb. 1967.
4. Spitzer, L., Jr.: Astronomical Research with the Large Space Telescope. (Based on the LST committee report, The Scientific Uses of a Large Space Telescope.) Science, vol. 161, July 19, 1968, pp. 225-229.
5. Kopal, Z.: Tasks for the Manned Orbital Telescope. Astronaut. Aeron., vol. 3, no. 12, Dec. 1965, pp. 16-21.
6. Tifft, W. G.: Astronomy, Space, and the Moon. Astronaut. Aeron., vol. 4, no. 12, Dec. 1966, pp. 40-53.
7. Orbital Astronomy Support Facility (OASF) Study. Vol. III, Task B—Instruments for Orbital Astronomy. Douglas Missile and Space Syst. Div., McDonnell-Douglas Corp., Rept. DAC-58143 (in support of Contract NAS-8-21023), June 28, 1968.
8. Large Space Structures Experiments for AAP. Midterm presentation. Gen. Dynamics, Convair Div., (Contract NAS-8-18118), Mar. 1, 1967.
9. Nilson, M. C.: Potential Orbital facilities for Soft X-ray and Long-Wave Radio Astronomy. Presented at 125th meeting of Am. Astron. Soc. in Philadelphia, Dec. 4-7, 1967 (abstract in Astron. J., vol. 73, no. 2, pt. II, 1968, p. 528).
10. Haddock, F. T.: Engineering Feasibility Study of a Kilometer-Wave Orbiting Telescope. Phase I. Final Rept. NGR-23-005-131, Univ. of Michigan (Ann Arbor, Mich.), Oct. 1966.
11. Kraushaar, W.: Study of Manned Space Investigations in X- and Gamma-Ray Astronomy. Final Rept. NGR-50-002-047, Jan. 1, 1966.
12. Dicke, R. M.: Scatter-Hole Cameras for X-rays and Gamma Rays. Astrophys. J. (letters), vol. 153, Aug. 1968.
13. Hanbury-Brown, R.; Davis, J.; and Allen, L. R.: The Stellar Interferometer at Narrabri Observatory—I. Mon. Not. Roy. Astron. Soc., vol. 137, no. 4, 1967, pp. 375-392.
14. Miller, R. H.: Measurement of Stellar Diameters. Science, vol. 153, Aug. 5, 1966, pp. 581-587.
15. Princeton Advanced Satellite Study. Final Rept. 8346, Perkin-Elmer Corp. (Subcontract 1 to NASA Grant NGR-31-001-044), May 1966.
16. Systems Study of a Manned Orbital Telescope. Midterm Rept. D2-90747-1, Boeing Co. (Contract NAS-1-3968), May 1965.
17. A System Study of a Manned Orbital Telescope. Boeing Rept. D2-84042-1 (in support Contract NAS-1-3968), Oct. 1965.

18. A System Study of a Manned Orbital Telescope, Synchronous Orbit Study. Boeing Rept. D2-84042-2 (Contract NAS-1-3968), Apr. 1966.
19. Orbital Astronomy Support Facility (OASF) Study. Vol. I–Technical Summary. Douglas Missile and Space Syst. Div., McDonnell-Douglas Corp., Rept. DAC-58141 (Contract NAS-8-21023), June 1968.
20. Orbital Astronomy Support Facility (OASF) Study. Vol. IV, Task C–Orbital Astronomy Support Facility Concepts. Douglas Missile and Space Syst. Div., McDonnell-Douglas Corp., Rept. DAC-58144 (in support Contract NAS-8-21023), June 28, 1968.
21. Optical Technology Experiment Systems. Phase II–Final Technical Report. Lockheed Missiles and Space Co. Rept. LMSC-A848294 to Perkin-Elmer Corp. (in support Contract NAS-8-20255), Sept. 1967.
22. The Needs and Requirements for a Manned Space Station. Vol. I–Summary Report; Vol. II–Astronomy. NASA Space Sta. Requirements Steering Com., Nov. 15, 1966.
23. 1967 Summer study of Lunar Science and Exploration. Univ. of California (Santa Cruz, Calif.), July 31-Aug. 13, 1967, NASA SP-157, 1967.
24. NASA 1965 Summer Conference on Lunar Exploration and Science. (Falmouth, Mass.) July 19-31, 1965, NASA SP-88, 1965.
25. Research Program on Radio Astronomy and Plasma for AAP Lunar Surface Missions. Final Rept. SID-66-381 (in support Contract NAS-8-20198), May 31, 1966.
26. Phase-A Study Optical Technology Apollo Experiment System (OTES). Vol. I. Perkin-Elmer Corp. Rept. 8900 (in support Contract NAS-8-20255), Oct. 1967.
27. Orbital Astronomy Support Facility (OASF) Study. Vol. V–Research and Technology Implications for Orbital Astronomy. Douglas Missiles and Space Syst. Div., McDonnell-Douglas Corp., Rept. DAC-58145 (in support Contract NAS-8-21023), June 28, 1968.
28. Program Memorandum, Astronomy. NASA Astron. Working Group, Sept. 3, 1968.
29. Report of the ASTRA Advisory Committee. July, 1968.
30. Hallam, K. L.: Proposal for a Manned Astronomical Space Telescope for the Post-Apollo Period. GSFC X-613-67-560, Nov. 1967.
31. Orbiting Astronomical Observatory with an Advanced Princeton Experiment Package Associated with Apollo Applications Program. Final study, Grumman Aircraft Eng. Corp. Rept. ASR-252D, for Perkin-Elmer Corp., Apr. 1960.
32. Optical Astronomy Package Feasibility Study for Apollo Applications Program. Vols. I and II. Final Kollsman Instr. Corp. Rept. (in support Contract NSA-8-20132), Mar. 1966.
33. Code, A. D.: Stellar Astronomy from a Space Vehicle. Astron. J., vol. 65, June 1960, pp. 278-284.

34. Goldberg, L.; and Dyer, R. E., Jr.: The Sun (ch. 17) and Galactic and Extragalactic Astronomy (ch. 18). In Science in Space, L. V. Berkner and H. Odishaw, eds., McGraw-Hill Book Co., Inc., 1961.